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Long-Term Diagnostics of the Condition of the Choli Minaret in Erbil Using Photogrammetry and Laser Scanning

Karel Pavelka, jr [1], Lukáš Běloch[1]

[1] Czech Technical University in Prague, Faculty of Civil Engineering, department of geomatics, Czech Republic
karel.pavelka@cvut.cz, lukas.beloch@cvut.cz

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Abstract

Long-term documentation of historic monuments is essential for their preservation. This paper presents nearly twenty years of monitoring the 14th-century Choli Minaret in Erbil (Iraqi Kurdistan) using photogrammetry, geodetic methods, and modern laser scanning. Initial surveys in 2006–2008 established a detailed 3D model and control network, enabling evaluation of structural stability and supporting the subsequent restoration in 2009. A new campaign in 2025 employed a Trimble X7 laser scanner and photogrammetry, yielding datasets several orders of magnitude denser than earlier surveys. Comparison with previous measurements revealed no significant deformation or inclination of the minaret, with deviations remaining within tolerance (±2 cm) and surface roughness limits. The study confirms the structural stability of the monument but highlights persistent moisture issues at the base as a potential risk. The results demonstrate the value of long-term geodetic and photogrammetric monitoring, while also enabling future applications such as digital twins and VR/AR visualization for heritage conservation.

1. Introduction

The precise and long-term documentation and analysis of historical objects is crucial for their future (Kovacs, 2015, Lee et al, 2025). There are many technologies how can make it, using photogrammetry, remote sensing, laser scanning, classical geodetical measurement or by geophysical methods (Boboc et al,2013, Fassi et al, 2019, Fraser, 2013, Hassani, 2015, Pavelka, jr.,Pacina, 2023, Kersten et al, 2012). This article discusses the long-term, twenty-year diagnosis of the condition of the historic Choli minaret in Erbil (Iraqi Kurdistan) using photogrammetry and laser scanning methods. The result of the diagnosis is the monitoring of the condition, and particularly the tilt of the minaret, which is visible and, if significantly increased due to an earthquake or other causes, could lead to the destruction of the structure. The result of modern building documentation is the possibility of using data for digital twins and visualization using VR/AR technologies (Pavelka,jr, Landa, 2024). This allows for the diagnosis of a building without a direct visit to the site, which reduces costs and carbon footprint.

The Minaret Choli, a 14th-century structure, is the last remaining element of a historic mosque and one of the most important monuments of Kurdish heritage. In 2005, its condition was critical due to the noticeable tilting of the upper part and the destruction of decorative elements. This was due to water leakage into the structure, surrounding terrain interventions, and insufficient maintenance. The original top of the minaret had long been lost, leaving the structure exposed to the elements, especially rainwater. The minaret has a seven-sided base approximately 12 meters high, on which stands a 24-meter-high cylindrical tower with a double spiral staircase. Despite the damage, valuable remains of historical plaster and stucco decorations have been preserved, especially in the niches of the lower part. However, these elements are severely damaged by weathering and mechanical damage. In 2005, it was decided to restore the monument, and in 2006, two Czech missions visited Erbil to document the monument, conduct archaeological research, and investigate suitable restoration techniques. First, detailed photogrammetric and geodetic documentation work was carried out using calibrated digital cameras and a total station. The results were a 3D model for static analysis, an animated model with photo textures, detailed photographic plans of the lower part, and a developed view of the upper part of the tower. The results of this mission were published at the CIPA symposium in Athens in 2007 (Pavelka et al, 2007).

2. Project Choli

In June 2006, general documentation of the Choli minaret in Erbil was carried out using photogrammetry. Supporting geodetic measurements were used to define the shape of the minaret and identify control points on the surface of its walls.

A local geodetic network was created and aligned using the Groma geodetic program. From the network points, detailed points on the object and control points marked with metal tags were gradually surveyed. The micro-network points were stabilized with a concrete foundation and a ceramic plate with a geodetic point, and with a steel rod in the paved areas.

Four polygon points (4001-4004) were selected in the vicinity of the minaret, from which 595 detailed points were surveyed, many of which were used as control points for photogrammetric surveying and evaluation. The polygon points were also surveyed using a low-accuracy Trimble GPS for orientation to the cardinal directions; an RTK system with corrections could not be used. A Trimble 5000 total station with a self-reflecting laser rangefinder was used for geodetic measurements. All points were surveyed with the same accuracy, with a spatial mean error of less than 1 cm. Artificial markings were used in the lower part of the minaret – crosses on individual walls. Naturally marked points were used on inaccessible parts of the minaret. After calculation, all points were displayed in the ACAD system (geodetic survey points), providing an accurate basis for photogrammetric evaluation of other parts of the object. The general shape of the minaret, including the cylindrical part, was thus measured.

The photogrammetric survey was performed using a calibrated Rollei6006 film camera and a calibrated Canon 20D professional digital camera with a resolution of 8MPix. The photogrammetric survey was used to create detailed photo plans of individual walls, followed by the development of the outer wall of the minaret tube and, finally, a detailed spatial evaluation based on intersection photogrammetry (Photomodeler). The average errors at the control points were within 2 cm, and the accuracy of the detailed points was 2-5 cm, depending on the possibility of identifying individual points in the images. The results were exported to MicroStation and then to ACAD, where the vector model was edited, sections were created, and the entire model was rendered using both artificial textures and real textures from photographs.

In 2008, reconstruction of the minaret was started by the Czech company GemaArt International (Pavelka et al, 2023). In October 2008, further measurements were carried out, focusing mainly on verifying the statics of the building and defining the immediate surroundings of the minaret. Since the above-mentioned geodetic micro-network was not used for long-term stabilization and no control measurements were subsequently carried out, a new micro-network was created in approximately the same configuration. Metal markers were mounted on the facade and stabilization points for the geodetic tripod were regularly built from concrete foundations in the surrounding terrain. Both measurements (June 2006 and October 2008) were performed using the same high-quality Trimble 5000 total station.

In 2008, the body of the minaret was covered with scaffolding, and it was not possible to use the same control points as in 2006. For long-term static measurements, 10 stainless steel makers were inserted into the body of the minaret and one marker into the surrounding fence. In addition, four micro-network points were constructed in the park for heavy stabilization and additional points were added using iron geodetic rods in the interlocking paving.

The shape of the minaret was repeatedly measured, as was its immediate surroundings, to identify its condition and any inclination. Four vertical profiles were created to compare the angle of inclination of the upper part of the minaret over a period of more than two years (a total of 267 checked points measured).

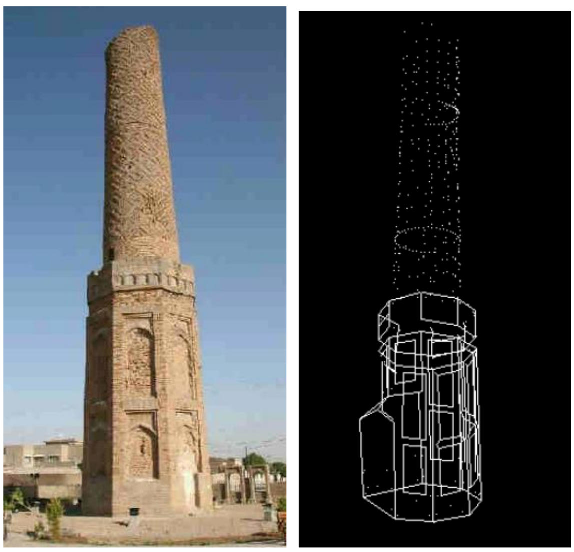


Figure 1: The Choli minaret in Erbil (2006-2008)

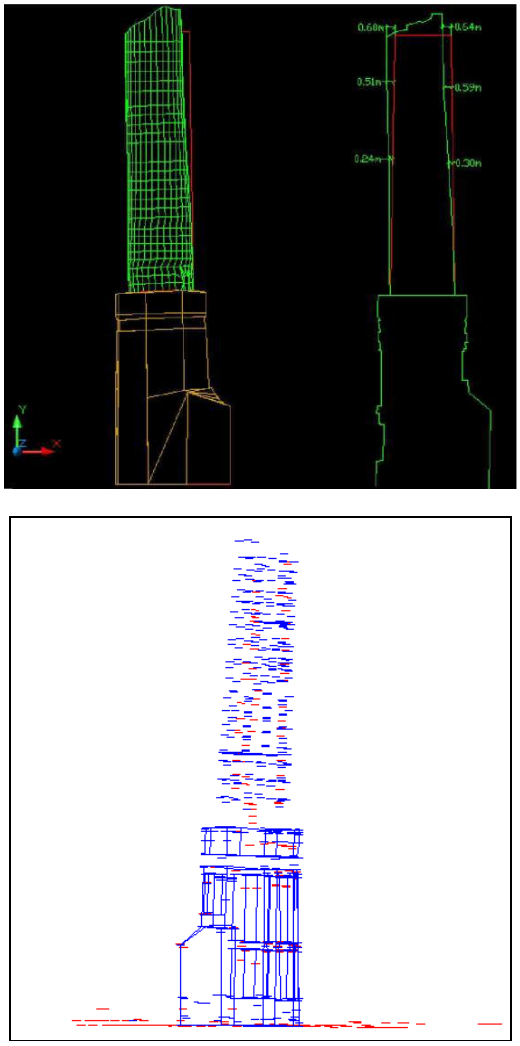


Figure 2: Computing of the tilt of the Choli minaret (deviation from the ideal axis by approx. 62-70 cm, upper part, 2006), Scheme of measured shape points (blue 2006, red 2008)

The focus was on static measurements, which were carried out on three consecutive days under different climatic conditions (sunny, 27 °C and 19 °C the following day); in total, two phases were re-measured on a system of control points with high accuracy. The differences in the successive measurement phases were only a few millimetres, and the influence of climatic changes was not significant.

The reconstruction was completed in 2009 with a recommendation for repeated measurements and maintenance (fig.1,2).

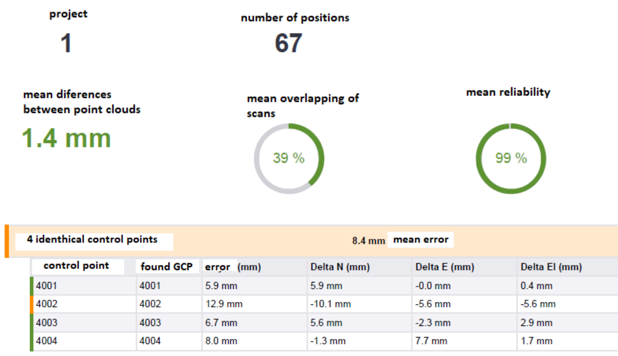
3. Data capturing ad processing

3.1 New measurement, 2025

In May 2025, a control measurement was carried out on request to determine the possible inclination of the minaret. The measurement was carried out using a precise Trimble X7 laser scanner with an accuracy of 3 mm in point position to determine the deformation of the minaret and its possible increased inclination. A photogrammetric measurement was also carried out to compare the condition since the last measurement. The condition of the minaret has changed slightly since its reconstruction in 2008–2009, the surroundings of the minaret have changed, the original stabilized points for geodetic measurements were no

longer visible, and the upper part of the minaret was not maintained in the same way as its immediate surroundings. In the end, a total of four of the seven original stabilized points were found, which can be considered a success. Their coordinates were known and therefore served as control points for new measurements, which were linked to the old measurements. Geodetic and photogrammetric measurements were performed using a Trimble X7 laser scanner, with a total of 67 positions used. For photogrammetric measurements, 798 photographs were taken using a Canon Mark D5 SLR camera. Processing was performed using Agisoft Metashape, CloudCompare, and Pix4D. A total of 20 GB of laser data and 4 GB of photographs were captured. In approximately 20 years, a million times more points were measured. This is truly a great advance. After comparing the data from the measurements taken in 2006 and 2008 and evaluating the detailed points on the minaret, it can be concluded that since the last measurement, there have been no significant changes in shape, significant deformations or tilting of the structure with an accuracy of 1 cm.
After comparing both phases of the measurements from four stable points towards the stainless-steel control points attached to the minaret shell, which are affected by temperature changes, differences in the order of millimetres (in two cases up to 16) were found. All are within the expected recording accuracy tolerance and are caused by the measuring technique and temperature changes. A comparison of the new measurements with the old measurements showed that the minaret body is stable and the deviations are within the tolerance limits of the measurement and surface roughness of the structure, where the spatial differences reach up to +/-5 cm. A comparison of the new and old measurements showed good agreement, although the old measurements have several orders of magnitude fewer detailed points due to the different measurement technology. However, the accuracy of the point measurements is similar, and the comparison of accuracy is good. Most deviations are within 2 cm, which is within the measurement accuracy and surface roughness (fig.3-5).

Figure 3: The stay of the Choli minaret in 2025



control point	found GCP	error (mm)	Delta N (mm)	Delta E (mm)	Delta El (mm)
4001	4001	5.9 mm	5.9 mm	-0.0 mm	0.4 mm
4002	4002	12.9 mm	-10.1 mm	-5.6 mm	-5.6 mm
4003	4003	6.7 mm	5.6 mm	-2.3 mm	2.9 mm
4004	4004	8.0 mm	-1.3 mm	7.7 mm	1.7 mm

Figure 4: From the measurement and adjustment report (Trimble); georeferencing on old found control points was very good with mean error 8.4mm and it can be better with more found control points. The control point Nr.4002 was an iron pole in interlocking paving only and has a lower accuracy.

Figure 5: Used laser scanner Trimble X7, (upper part), point cloud from measurement, photo from one of 67 scanner position (left) and deformation of the upper part of minaret (right)

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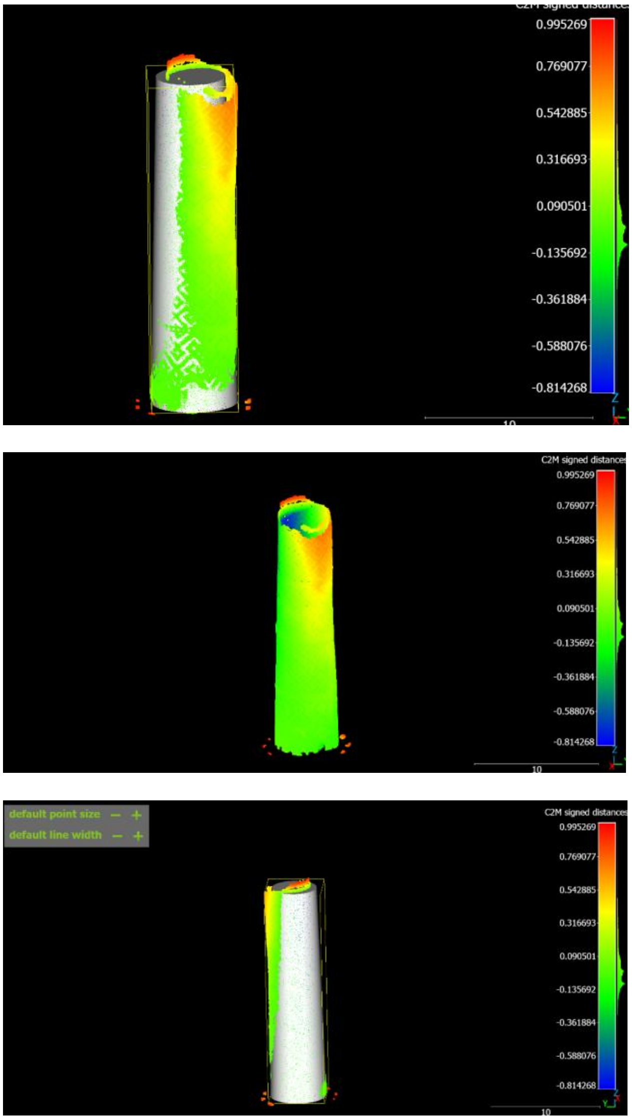

Figure 6: Comparison with an idealized body, deviation from verticality reaches max. 70 cm, which is in good agreement with the original measurement

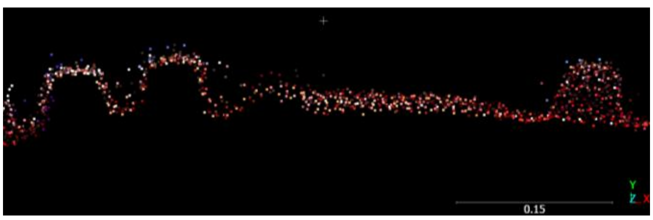

Figure 7: Spatial variation of the minaret surface +/- 5 cm; this is important for assessing minor deviations.

The cloud was fitted to the points found, and the georeferencing deviation is in the measurement log. The control point numbers were renumbered because not all the original points could be found. The point numbers are: 4001 = 4001, 4004 = 4003, 4002 = 4004, 4003 = 4005.
The points on the minaret marked with markers were checked, a total of 3 on the lower base (fig.6-12).

These were the points that were found and renumbered, as it was not possible to find all of them:
1 = 9, 2 = 8, 3 = 2.
Point deviation x, y, z in meters
1 -0.002 -0.005 0.003
2 0.005 -0.002 0.006
3 -0.015 0.002 -0.001

The measurements indicate that the base of the minaret has not tilted within the accuracy of the alignment to the original registration points from the original measurement.
Furthermore, a c2c comparison was performed in CloudCompare software, where the original points were compared with the newly measured point cloud using c2c.

The result is Histogram_deviations.png (Fig. 10)

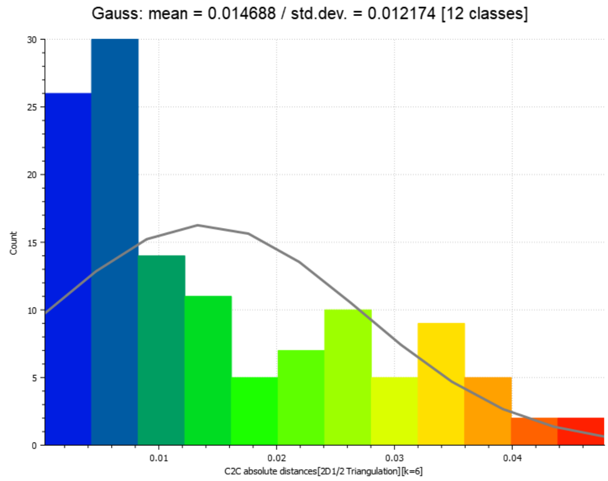

Figure 8: Histogram of minaret´s deviations between 2006, 2008 and 2025, only a few centimetres

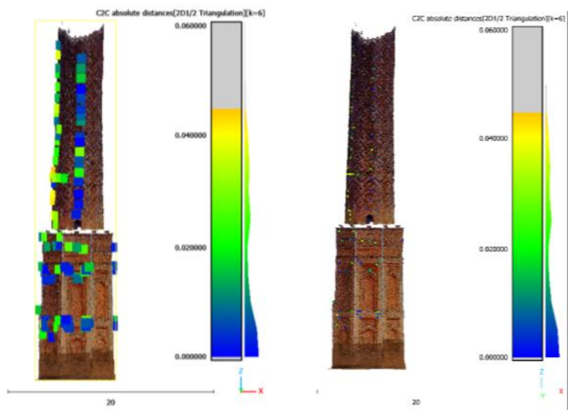

Figure 8: View from the south

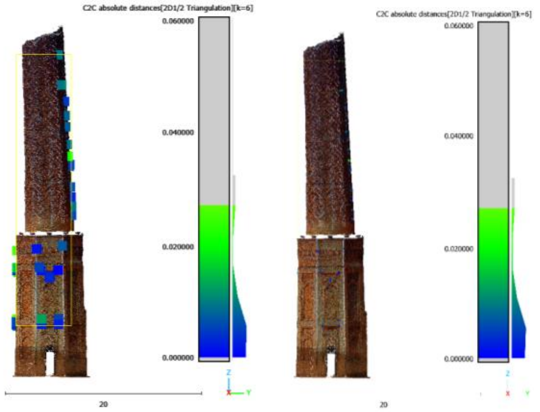

Figure 9: View from the east

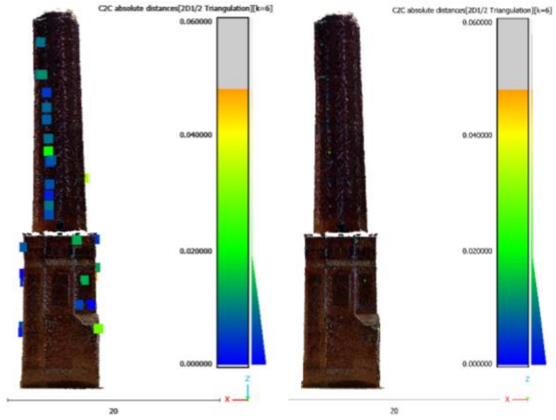

Figure 10: View from the north

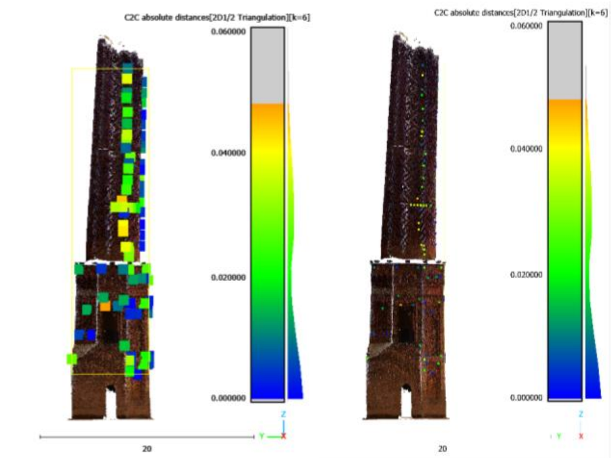

Figure 11: View from the west

Figure 12: QR code for AR model (iOS only)

Given the detailed documentation of this valuable monument, a 3D textured mesh model was created, which can be viewed using a QR code (fig.12). For now, AR visualization only works for iOS (Mužík, 2025, Pavelka et al., 2025).

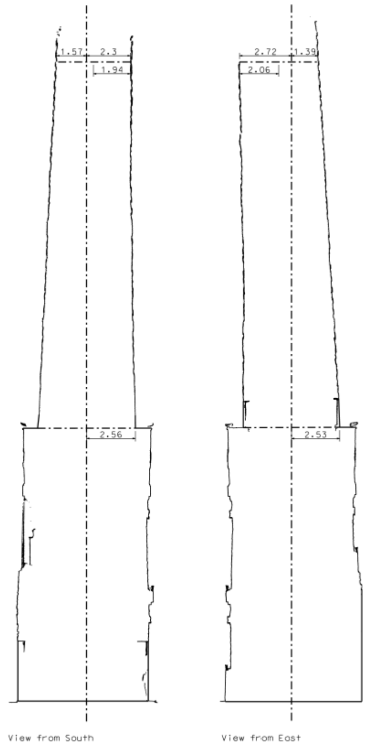

Figure 13: Cross-section with tilting. Maximal tilting in cross-section South-North is 0.36-0.37m, Maximal tilting in cross-section East-West is 0.66-0.67m. This is in good accordance with the old measurements, which were not as detailed.

3.2 Summary

1) After comparing the data from measurements taken in 2006 and 2008 and evaluating the detailed points on the minaret, it can be stated that since the last measurement, with a measurement accuracy of 1 cm, there have been no significant changes in shape, significant deformations or inclination of the structure.
2) After comparing both phases of the measurements from four stable points towards the stainless-steel control points fixed to the minaret shell, which are affected by temperature changes, differences in the order of millimetres (in two cases up to 16) were found. All are within the expected recording accuracy tolerance and are caused by the measuring technique and temperature changes.
3) Comparison of the new measurement with the old measurement showed that the minaret body is stable and the deviations are within the measurement tolerance limits and the surface roughness given by the structure, where the spatial differences reach up to +/-5 cm. A comparison of the new and old measurements showed good agreement, although the old measurements have many more orders of magnitude fewer detailed points due to the different measurement technology. However, the accuracy of the point measurements is similar, and the accuracy comparison is of good quality. Most deviations are within 2 cm, which is well within the measurement accuracy and surface roughness.

Figure 14: The moisture clearly visible at the base of the minaret (left up), a very good condition of minaret part, no cracks are visible

Figure 15: Upper part of minaret in 2025 and in 2009

4. Conclusion

The main result of this long-term project is that the geodetic measurements did not show any systematic tilt of the minaret body or any other deformations within the range of the accuracy and type of measurement based on a comparison of the measurements from 2006 and 2008 with the new measurements from 2025. The Choli minaret is not tilting and has not deformed in any way between 2006 and 2025.
However, the moisture clearly visible at the base of the minaret is problematic and may cause certain shifts or static problems in the future. Its origin is described in the report given to the local authority(fig.14-15).
From the geodetical point of view it can be stated that the today condition of the Choli minaret is stable and comparable to the condition in 2006.

Acknowledgments

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